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MPS and Ionospheric Propagation Codes

Max Light
9 February, 2017



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Multiple Phase Screen Scintillation Code

EM Scintillation – Diffraction due to Ionospheric Irregularities

- **Natural phenomena**
 - **Plasma instabilities**
 - Rayleigh Taylor, Kelvin Helmholtz
 - **Charge-neutral viscosity –**
 - gravity/acoustic waves driven by, i.e., earthquakes, meteors, thunderstorms
- **Man Made**
 - **HANE**
 - **Chemical release**

MPS Formulation – forward scattering/diffraction

- Knepp, Proc. IEEE, vol. 71, No. 6, 1983, pp. 722-737
- Ionospheric electron density irregularities with scale sizes less than wavelength(s)
- Forward propagating EM wave propagates through ionosphere divided into discrete number of thin layers perpendicular to wave propagation direction
 - Does not track reflections
 - Can model quiescent up to fully disturbed ionospheric effects on signal propagation
- Electron density irregularities in each layer impart a random geometric optics phase change to each frequency component
- Phase change determined from statistical properties of the electron density irregularities
- Phase and amplitude fluctuations in the EM wave caused by phase change contributions

MPS Formulation – Parabolic Wave Equation (PWE)

- EM wave traveling mostly in z-direction, no variation in y-direction – paraxial approximation

$$E(x, z, \omega) = U(x, z, \omega) e^{-i k z}$$

$$\left| \frac{\partial^2 U}{\partial z^2} \right| \ll k \left| \frac{\partial U}{\partial z} \right|$$

- EM wave equation becomes the parabolic wave equation

$$\frac{\partial^2 U}{\partial x^2} - 2 i k \frac{\partial U}{\partial z} + 2 k^2 \Delta \epsilon(x, z, \omega) \cdot U = 0$$

- Where the change in refractive index (from free space to medium) is

$$\Delta \epsilon = 8.98 \times 10^{-16} \cdot \Delta n_e$$

electron density

PWE - Split Step Recursive Solution

- In free space

$$\Delta \epsilon \rightarrow 0$$

$$\frac{\partial^2 U}{\partial x^2} - 2ik \frac{\partial U}{\partial z} = 0$$

Fourier transform in perpendicular Direction (x), and solve for U

$$U(k_x, z_2, \omega) = U(k_x, z_1, \omega) e^{i \frac{k_x^2}{2k} \Delta z}$$

- In medium

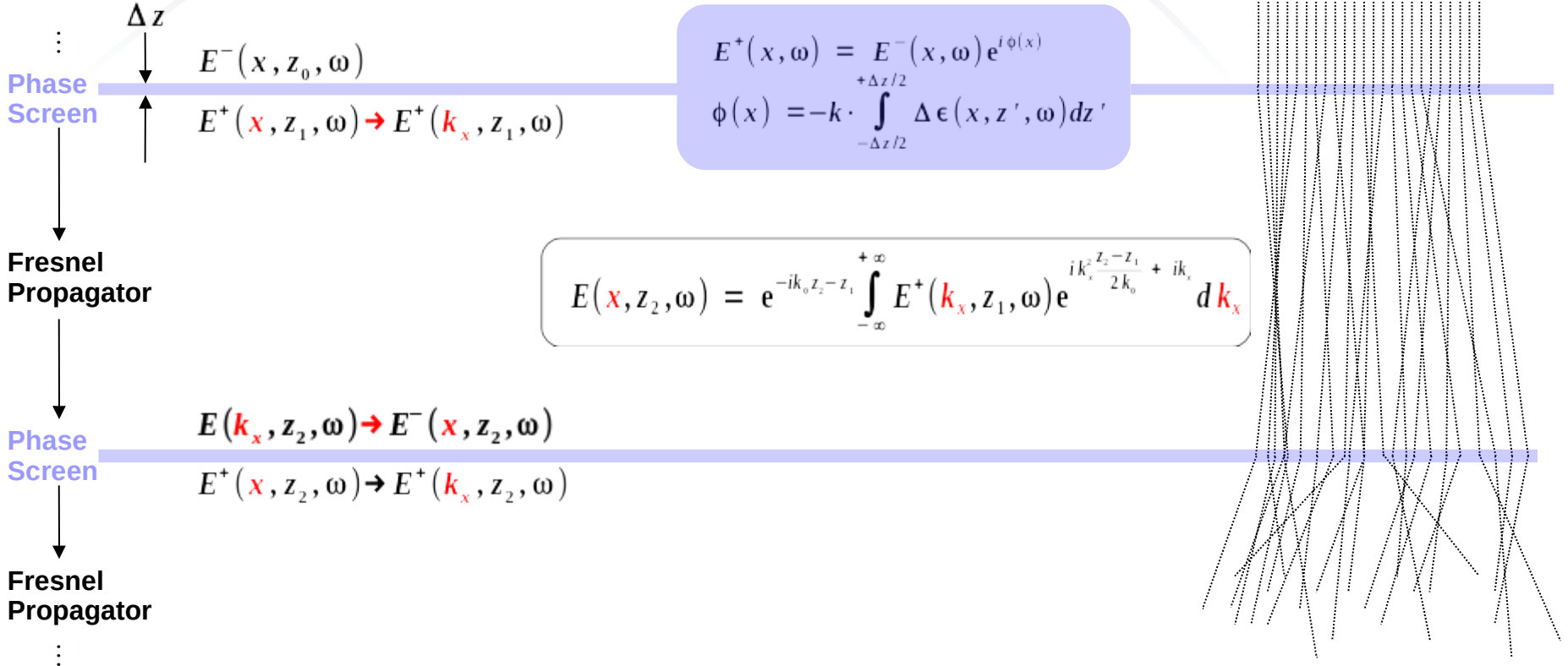
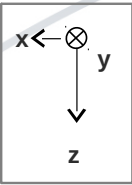
$$\frac{\partial^2 U}{\partial x^2} \rightarrow 0$$

$$- 2ik \frac{\partial U}{\partial z} + 2k^2 \Delta \epsilon(x, z, \omega) \cdot U = 0$$

Inverse transform U and apply
Phase contribution

$$U(x, +\Delta z/2, \omega) = U(x, -\Delta z/2, \omega) \cdot e^{-ik \cdot \int_{-\Delta z/2}^{+\Delta z/2} \Delta \epsilon(x, z', \omega) dz'}$$

PWE - Split Step Recursive Solution



Phase Screen Generation

- spatial autocorrelation function of the phase screen contribution is related to the spatial autocorrelation function of the density irregularities perpendicular to the direction of propagation*

$$B_{\phi}(\xi) = \langle \phi(x) \phi^*(x+\xi) \rangle = r_e^2 \lambda^2 \Delta z \int_{-\infty}^{+\infty} B_{n_e}(\xi, z') dz'$$

classical electron radius
 $r_e = 2.82 \times 10^{-15} \text{ m}$

- Fourier transform gives respective PSD's
- 1D phase contribution PSD of phase screen contribution is related to the density fluctuation PSD* → Generate phase screen from Fourier transform of density fluctuation PSD

$$S_{\phi}(k_x) = 2\pi r_e^2 \lambda^2 \Delta z \cdot S_{n_e}(k_x, k_z=0)$$

* Salpeter, E.E., Astrophys. J., 147, pp. 433-448, 1967

Phase Screen Generation

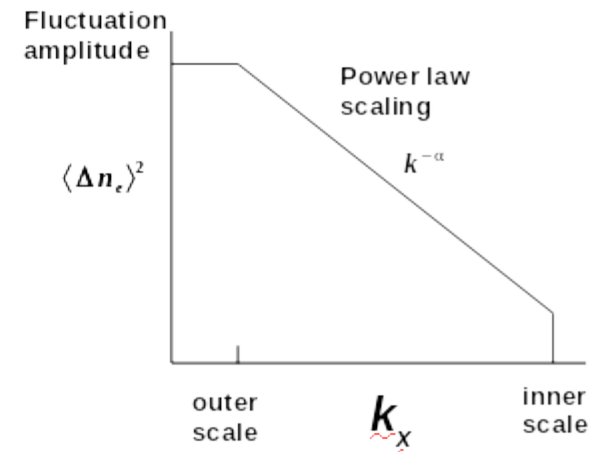
- Begin with Gaussian random variable

$$\phi = \sqrt{2} r_j \sqrt{-\ln(P)/P} \quad P = r_1^2 + r_2^2 \quad \langle r_j \rangle = 0 \quad \langle r_j \rangle^2 = 1$$

- Take Fourier transform

- Multiply by spectral scaling law (irregularity PSD), known apriori

- Take inverse transform to find phase screen function $\phi(x)$



Phase Screen Generation

- $\langle \Delta n_e \rangle^2$ is related to the coherence bandwidth and coherence length, which are inter related through the Fresnel propagator and geometry
- Most common measurement is the scintillation index, S_4 , which is related to the coherence length and coherence bandwidth (stationary random processes and ergodic assumption)

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle \langle I \rangle}{\langle I \rangle}}$$

- Mapping between S_4 and $\langle \Delta n_e \rangle^2$ is usually found empirically

Current MPS Model and Development Plans

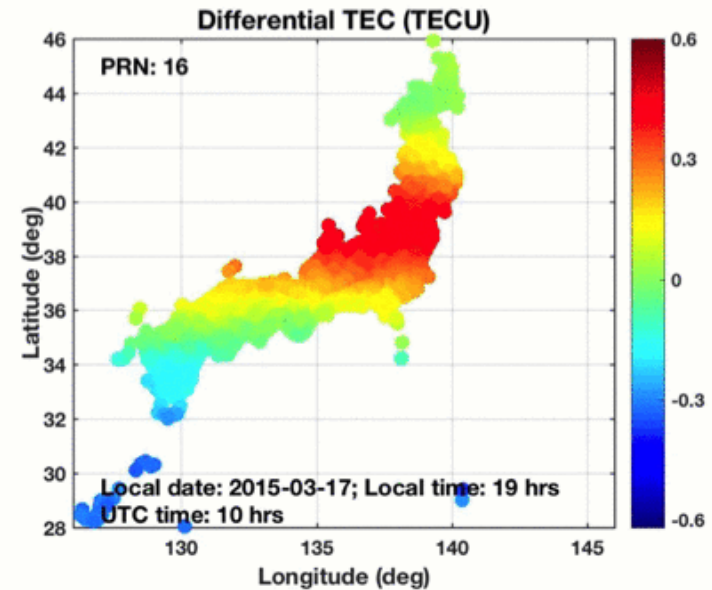
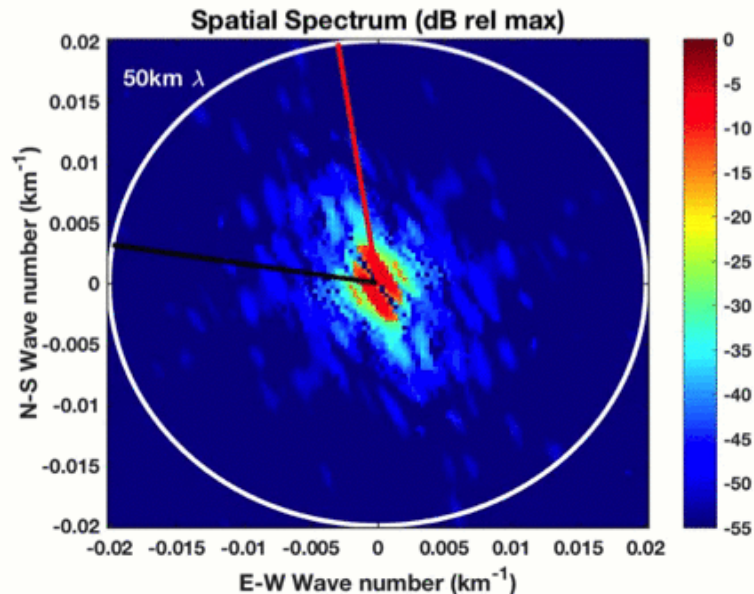
- **1D Phase screen with power law scaling between inner and outer scale lengths.**
 - **After Knepp, accurate for field-aligned irregularity structure**
- **Employed as a scintillation module after a signal has propagated through the ionosphere**
- **Predict scintillation parameters either along or across the magnetic field using 1D phase screen with concomitant irregularity PSD (if available)**
- **2D irregularity PSD measurement for use in MPS code currently underway in a separate LANL LDRD effort**

Current MPS Model and Development Plans

- One goal of current validation experiment is to specify, in situ, the shape of the ISD.
- Once known, iterate on measured S_4 using MPS code.

Current MPS Model and Development Plans

- 2D irregularity PSD characterization using GPS TEC receivers



LANL Ionospheric Propagation Codes

**Implemented as frequency dependent,
wide bandwidth, Ionospheric Transfer Function (ITF).**

Transionospheric Propagation - homogeneous slab

- **Definite top and bottom altitudes**
- **No variation in electron density or magnetic field**
 1. **Taylor expansion of refractive index ($f \gg f_p, f_{ce}$) with and without magnetic birefringence - LOS: all rays reach satellite.**
 2. **Two dimensional Snell's law in spherical geometry (Bourger's) - solve analytically for rays that reach satellite at each frequency.**
- **(1) and (2) are currently implemented**

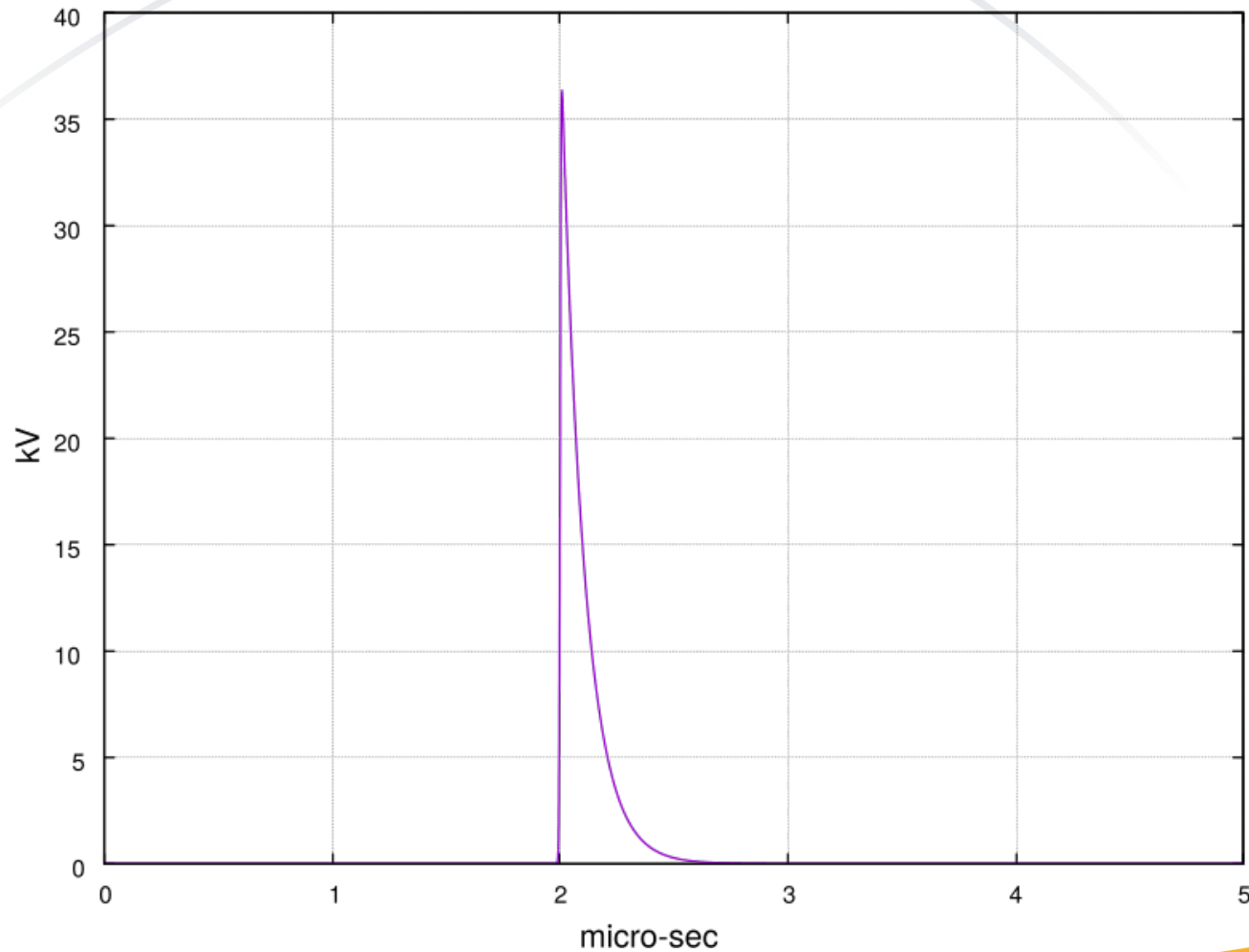
Transionospheric Propagation - nonhomogeneous (2D) slab

- Definite top and bottom altitudes
- Electron density and magnetic field vary with altitude (r) only – no gradients in other directions
 3. Two dimensional Snell's law in spherical geometry (Bourger's) – solve analytically for rays that reach satellite at each frequency, including $n_e(r)$ and $B_0(r)$ in calculation.
 4. Ray trace – WKB approximation (geometric optics). must iterate over frequency and angle.
 5. Divide ionosphere into spherical shells of constant n_e and B_0 . Match boundary conditions at each shell interface.
 6. Forward propagating or parabolic wave equations – Spherical shell solution method neglecting the Fresnel term. Must iterate over frequency and angle.
- (3) is in early stages of development. (4) can be implemented with 3D ray tracer (turn off gradients in theta, phi). (5) and (6) are not planned for implementation in this program

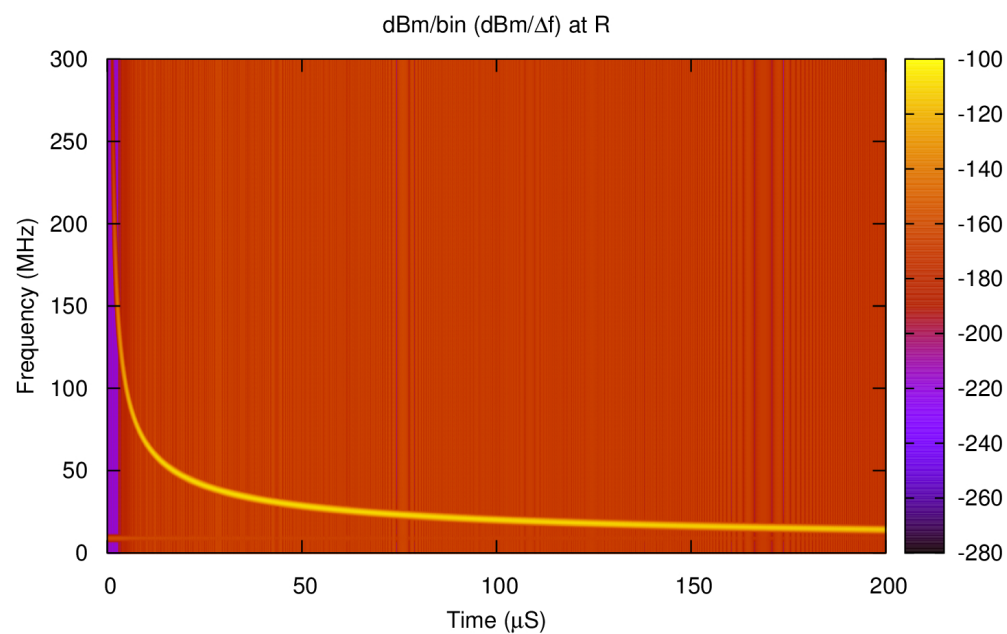
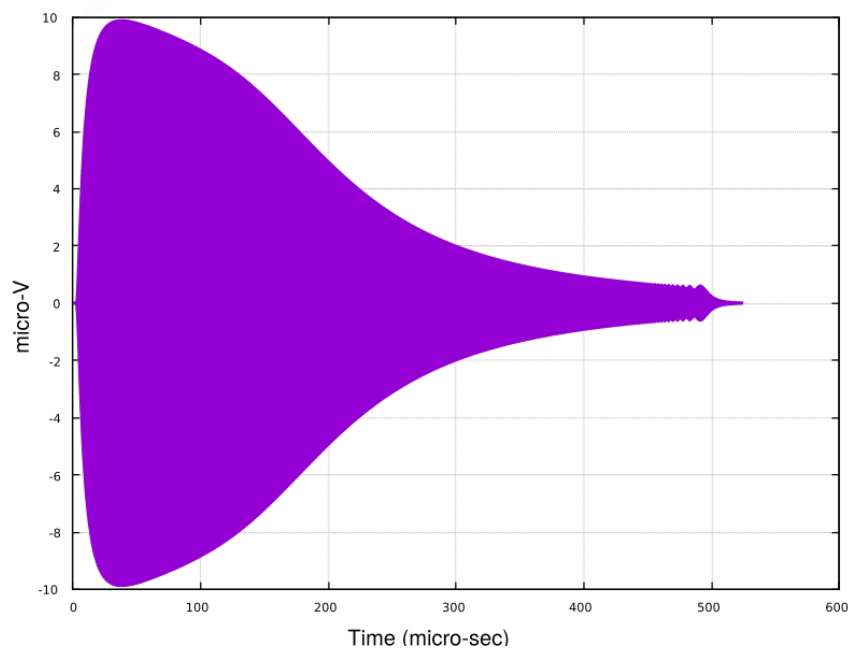
Transionospheric Propagation - fully 3D nonhomogeneous ionosphere

- Can have bottom and top altitudes, or not.
 - Electron density and magnetic field gradients in all directions – full description of ionospheric variations.
 - Horne, JGR, vol. 94, No. A7, pp. 8895 – 8909, 1989.
-
7. Ray trace – WKB approximation (geometric optics). Must iterate over all launch angles and frequencies.
-
- (7) is complete as a ray tracer, needs further development for implementation as an ITF

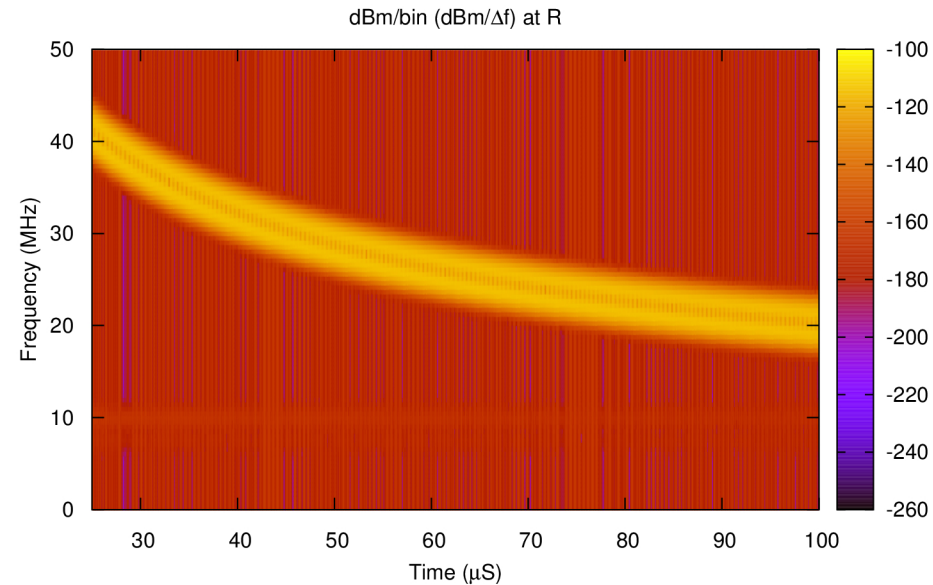
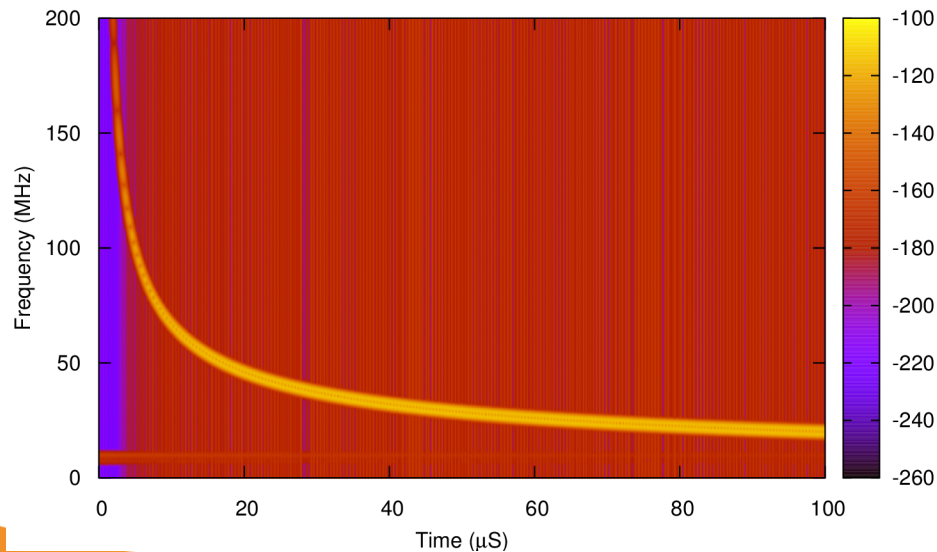
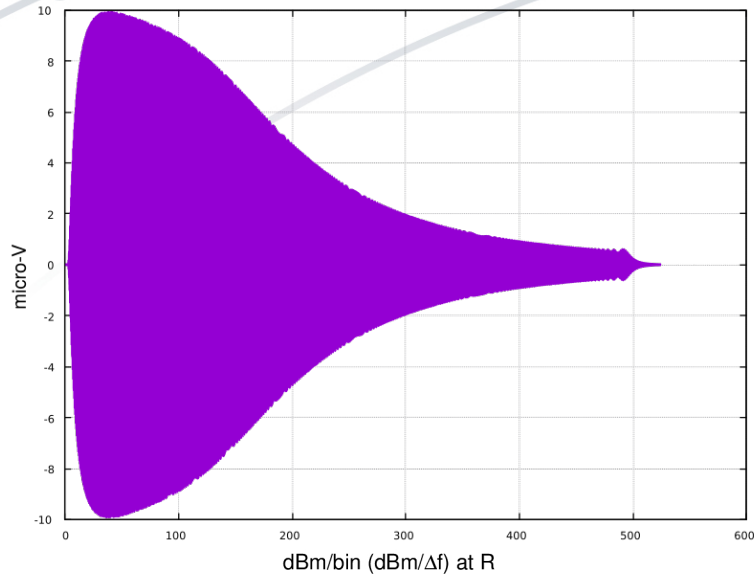
Transionospheric Propagation Example



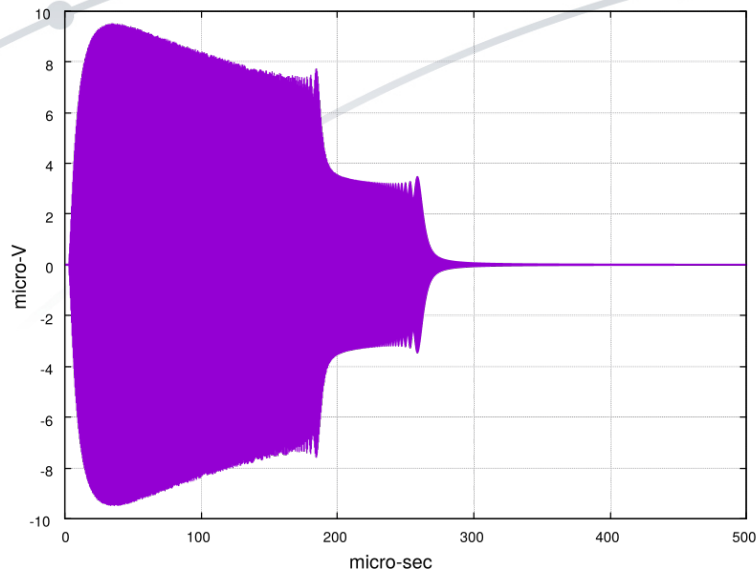
Direct LOS, No Birefringence



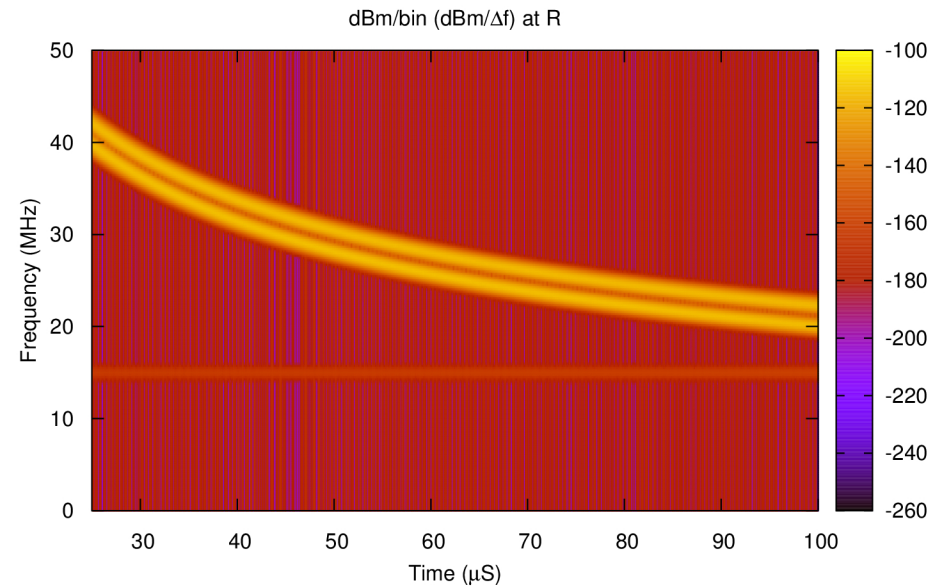
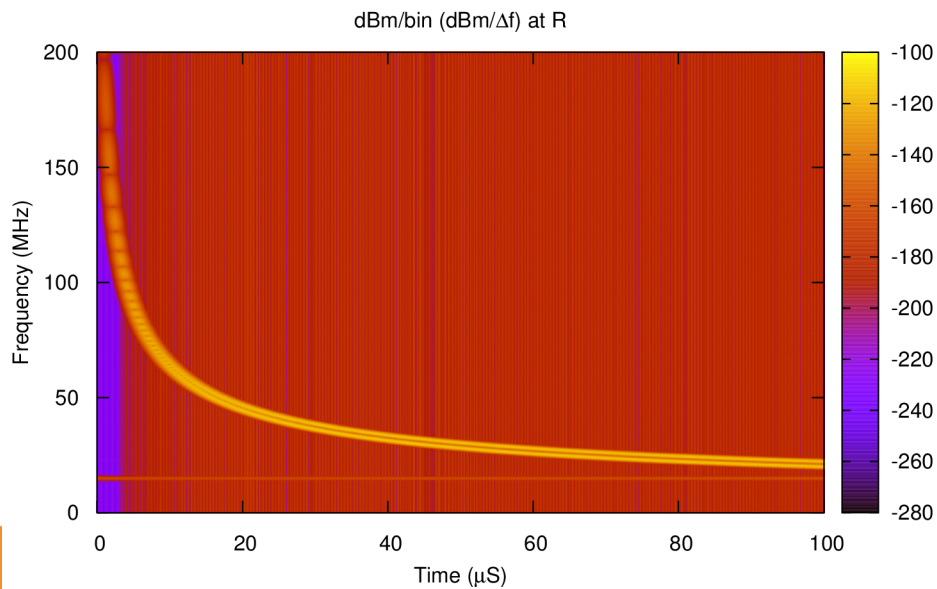
Direct LOS, Birefringence



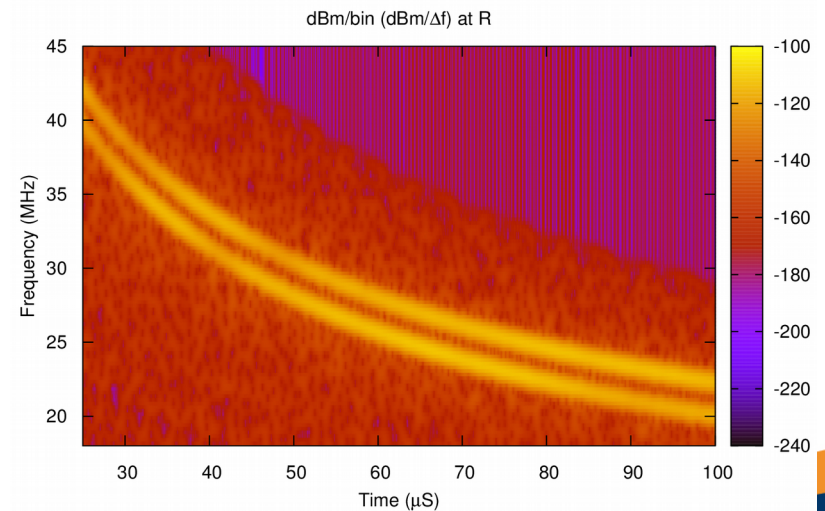
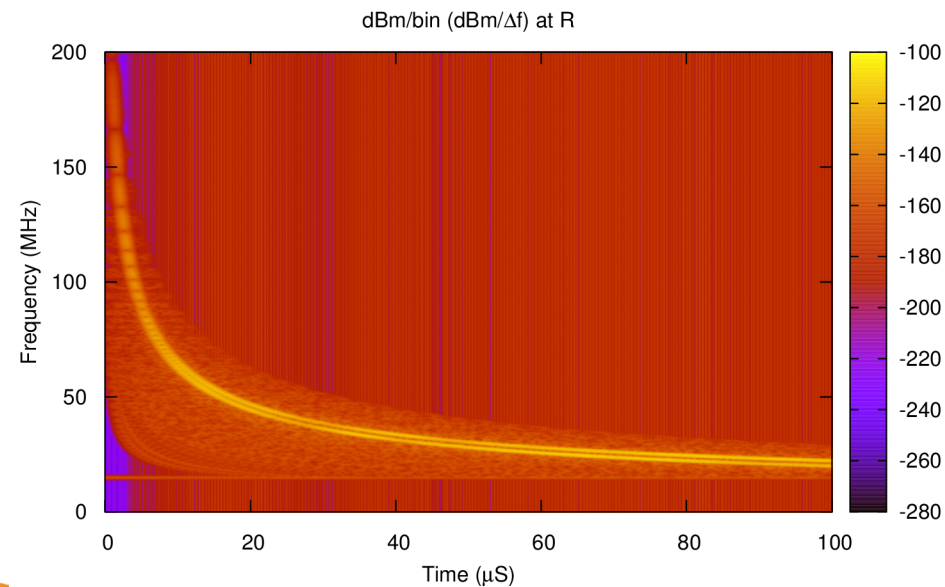
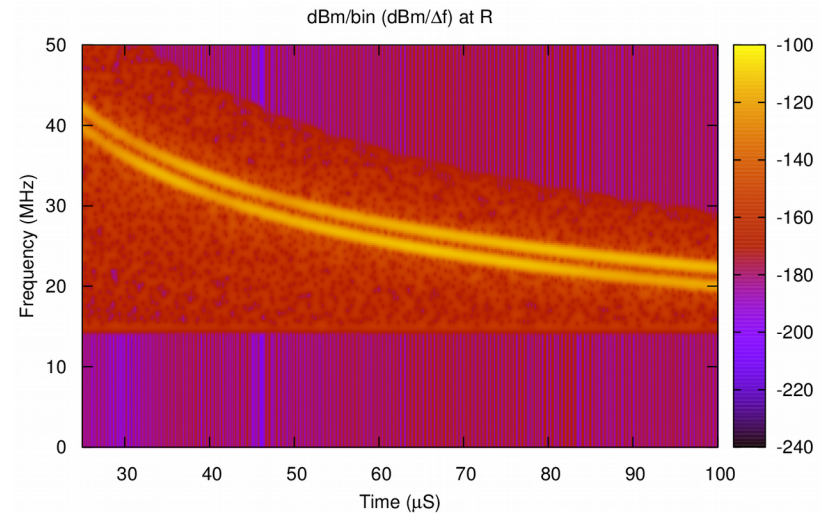
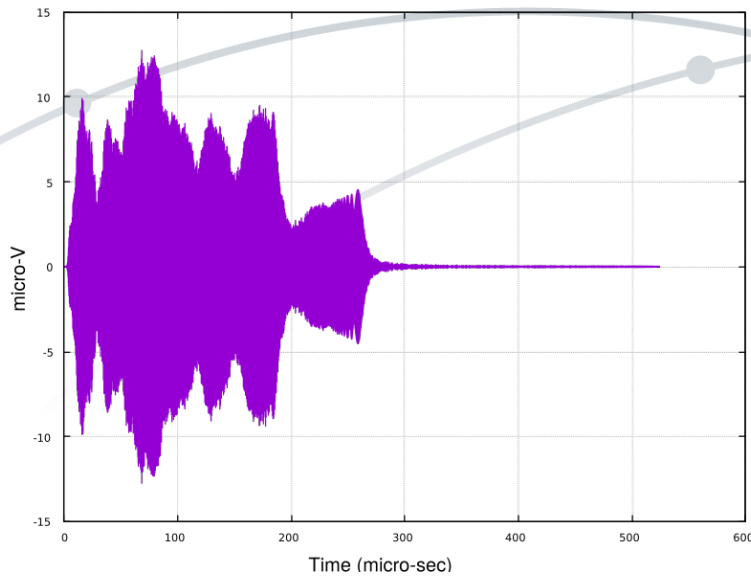
Slab Ionosphere



Lat, Lon
Source 35, 65
Sat 40, 70



Slab Ionosphere – highly scintillated ($S_4 = 0.84$)



Summary / Conclusions

- **ITF specified for multiple ionospheric propagation scenarios**
 - **LOS and slab ionosphere finished**
 - **Non-homogeneous 2D and full 3D ITF's being developed**
- **1D ISD MPS scintillation model complete**
- **MPS code extension to include 2D ISD effects underway (LDRD)**